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Thesis

THE CONSTITUENTS OF ATOMS
THEIR DISCOVERY, PROPERTIES, AND USES

by

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Outline

I. Introduction

The purpose of this thesis is to present the development of the atomic theory, from the view-point of the particles involved, giving the discovery, properties and uses of each, observing chronological order in presenting them, and also in the discussion of each individual particle.

II. The History of Atomic Theory.

It has been suggested, though not proved, that Pythagoras[1] presented a theory of the discontinuity of matter some time during the sixth century B.C. There are no written records to that effect. To Democritus, who lived in the fifth century B.C., usually goes the credit for the first atomic theory. In reality Democritus was but the pupil of the true founder, Leucippus. Dr. Robert A. Millikan has stated that the views of Leucippus might almost pass today. Democritus believed that within objects there are processes going on which, because of their minuteness, are forever hidden from sensuous perception.[2] The Latin poet, Lucretius, wrote a treatise, "De rerum natura," "Concerning the Nature of

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[1]Shipley, Maynard, The Origin and Development of the Atomic Theory, (1924), pp. 9-20.

[2]Haas, Arthur E., The World of Atoms, (1928), p.1.

Things," in which he expressed a belief that the subdivision of matter would lead to the atom.[1] The word atom means something which cannot be cut. Democritus believed, and modern science has proved, in a certain sense, that all atoms are built of the same kinds of units. To John Dalton must be given the credit for the modern chemical atomic theory, which he formed in 1803.[2] He had before that time adopted a physical atomic theory.[3]

By the atomic theory was meant that all matter is composed of extremely small particles (atoms) which are invisible, indivisible, unchangeable, and possess certain characteristic properties. This was the definition as presented by C. Baskerville in 1904. Dulong, Petit, Dalton and Mitscherlick all believed in indivisibility of atoms.

III. The Electron.

<u>The discovery of the electron</u>.

This idea, which named the atom as the indivisible particle of matter, was first doubted by Mendeléeff. However, Sir William Crookes was the "father" of modern

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[1]Bragg, Sir William, <u>Concerning the Nature of Things</u>, (1925), pp. 1-2.

[2]<u>Ibid</u>., p.3.

[3]Shipley, <u>op</u>. <u>cit</u>., p.59.

work on atomic structure. He discovered in 1870 the phenomenon of cathode rays.[1] With extraordinary intuition he called these rays the "fourth state of matter."

In 1874 Johnstone Stoney,[2] in addressing the British Association pointed out that it is almost a necessary consequence of Faraday's laws of electrolysis and of the atomic theory that electricity should be atomic in character, that is, that any charge of electricity must always contain an integral number of elementary charges, which cannot be further subdivided. It was Stoney who first suggested the name "electron" for one of these elementary charges. However, Stoney applied the term "electron" to an elementary charge of either sign.

Following this physicists found an electro-mechanical parallelism which gave rise to a series of new relations, the great fruitfulness of which became obvious when, in the year 1895, the Dutchman, Lorentz,[3] produced the electron theory. The theory of Lorentz is based on the idea of convection currents. It assumes that small electrical charges capable of motion are contained in

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[1]Hull, G. F., An Elementary Survey of Modern Physics, (1936), p.22.

[2]Jauncey, Modern Physics, (1932), p. 136.

[3]Haas, Arthur, The New Physics, (1930), p.51.

molecules, and that the alterations in their positions represent convection currents. On the basis of the electrochemical laws it further assumes that these charges, which Lorentz calls electrons, are each of the magnitude of one elementary electrical quantum.

In 1896 another Dutch scientist, Zeeman,[1] discovered the effect which bears his name and which consisted in the splitting up of a spectral line into numerous components in a magnetic field. This could be deduced purely by mathematics from the electron theory of Lorentz, thus being a brilliant experimental confirmation of the theory. A more detailed investigation of the Zeeman effect showed that the electrical particles must be negative. Measurement of the specific charge showed it to be about 1800 times greater than that for ionized atoms of hydrogen. Assuming each to have one elemental quantum of electricity, this lead to the supposition that the mass of the electron was 1800 times smaller than an atom of hydrogen - the smallest known mass at that time.

Following this J. J. Thomson and Oliver Lodge,[2] from experimentation, also insisted upon the existence

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[1]Haas, op. cit., p. 52.

[2]Baskerville, C., "Transmutation of the Chemical Elements," Independent, 57:1495-8, (Dec. 29, 1904).

of particles approximately a thousand times smaller than the lightest known chemical element, hydrogen, the former calling them electrons and the latter, corpuscles.

The former of these eminent English physicists went even a step further and endeavored to show that, after all, the electrons are simply embodied electricity, which was in keeping with the proposal of Stoney.

The determinations of the charge of the electron and the ratio e/m.

Thomson was the first and C. T. R. Wilson the next to measure the charge of the electron. Then Millikan refined the experiment. Thomson's experiment was as follows.[1]

A highly evacuated glass tube contained a cathode and an anode, the latter having a small rectangular slot in it through which the cathode rays might pass. Beyond the anode was a screen similar to the anode and electrically connected to it. Cathode ray particles were accelerated from the cathode toward the anode, and after passing through the anode, moved with uniform velocity and emerged from the slot in the screen as a small bundle of rectangular cross-section, which then passed between two parallel plates, and finally caused a small

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[1] Richtmyer, F. K., Introduction to Modern Physics, (1934), pp. 153-7.

phosphorescent patch on the end of the tube. When a potential difference, V, was maintained between the parallel plates, one of which was positive, the position of the spot was shifted and was below that when no potential difference was maintained. The curve of the deflected beam was a parabola when only the electric field was present. A pair of Helmholtz coils, whose diameters were equal to the length of the plates, were placed in front and behind the tube to produce a magnetic field perpendicular to the electric field, the strength of the field being determined from the dimensions of the coils and the current through them. The field was directed so that the spot was deflected upward by it. The two fields were then adjusted so as to counteract each other. Then the magnetic field was removed and the deflection measured. The ratio of e/m could then be determined. e' = the charge of the moving particle in electromagnetic units, m = the mass of the particle, d = the distance between the plates, F = V/d = the electric field between the plates, H = the magnetic field, v = the horizontal velocity (constant over the entire path from screen to spot, since there were no horizontal forces acting on the particle) with which the particles emerged from the screen. The downward force f_F, produced by the electrostatic field, was given by $f_F = F \cdot e'$. It was

equal and opposite to the upward force f_H due to the magnetic field and given by $f_H = He'v$. Therefore $He'v = Fe'$ or $v = F/H$. This gave a means of measuring the horizontal velocity with which the particles passed between the plates. This velocity was determined by the potential difference applied between the cathode and the anode, and, to a certain extent, by the vacuum. From the measurement of the deflection it was possible to determine the downward deflection, S, which the particles experienced in passing between the plates. The downward acceleration, a, = Fe'/m. <u>a</u> was constant over the length of the plates, l. t/2 was the time required to pass over l. Therefore $S = \frac{1}{2}F(e'/m)t^2$, where $t = l/v$ and $f_F = F \cdot e'$. All quantities were thus known except e'/m, which could be calculated. Thomson found it to be of the order of 10^7 and independent of the kind of gas (air, H_2, CO_2) in the tube and independent of the material of the electrodes (Al, Fe or Pt). A later determination gave 1.7×10^7, a value numerically almost identical with the value determined for particles taking part in the Zeeman effect, which particles therefore seemed to be identical with cathode rays.

This value of e'/m is very much larger (1700 times) than the value of e'/m for hydrogen atoms in electrolysis, which is 9650, and e was known to be of the order

of 10^{-20} e.m.u. or 10^{-10} e.s.u. This large value might result from either a large value of e', a small value of m, or both. H. A. Wilson measured e' by his cloud chamber and found it to be of the order of 1×10^{-20} e.m.u. or 3×10^{-10} e.s.u. Therefore this led to a small m rather than a large e. Assuming that the charge carried by the cathode particle is the same as that carried by the hydrogen atom in electrolysis, the mass of the cathode particles must be of the order of 1/1700 of the mass of the hydrogen atom, which was the smallest particle known up to the time of Thomson's experiments. He called them "corpuscles" or "primordial atoms". Thomson found the value of e to be the same as that for the hydrogen ion in electrolysis, so that the mass of the cathode particle as determined by him is 1/1847 of the mass of the hydrogen ion. Since the charge is the same as that on the hydrogen ion, Stoney's term "electron" began to be applied to the cathode particles.

Values taken from Birge, Review of Modern Physics, vol. I, pp. 59-63, give $e' = 1.591 \times 10^{-20}$ e.m.u., $e = 4.770 \times 10^{-10}$ e.s.u., $e'/m = 1.769 \times 10^{7}$ e.m.u./gm., $e/m = 5.303 \times 10^{17}$ e.s.u./gm.

Professor Schuster in 1889 was the first to apply the method of magnetic deflection of the discharge to get a determination of the value of m/e.

C. T. R. Wilson used charged water particles moving in an electric field.

Millikan[1] in 1909 used oil droplets. In his experiment two horizontal plates were placed about 1 cm. apart. Through a hole in the upper plate droplets of oil formed by an atomizer were allowed to fall. The droplets were so small they showed Brownian movement but could be seen as points of light in a microscope. When torn apart by the atomizer the droplets usually became charged with one, two or three electrons. If not, they could be charged by X-rays. The droplets drifted downward and could be attracted up or down by proper application of an electric field. Their individual weights were determined by the rate of fall, wt = $4/3\pi\rho r^3$. From Stokes' Law $v = 2g\rho r^2/9\eta$, where g is gravitational field, ρ = density, r = radius, and η = viscosity. A larger potential was kept between the plates than that required for equilibrium. Therefore, if a droplet ascended with a speed just equal to its earlier velocity of fall, the electric force was twice its weight; if the speed upward were twice the velocity of fall, the force was three times its weight. The electric force equalled qE, where q was the charge on

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[1]Eldridge, J. A., The Physical Basis of Things, (1934), pp. 124-6.

the drop, and this force equalled the mass of the drop. Therefore mg (the mass) = qE. (E was found by dividing the potential difference in e.s.u. by the distance between the plates.) q was found to be a small multiple of a certain value which was taken as the charge of a single electron. Millikan's value was 4.770×10^{-10} e.s.u.

Some values of the electronic charge which were obtained by various methods are given, with their authors, in the following table.

Author	Method	Value $\times 10^{-10}$ e.s.u.
Wilson	Water Cloud	3.
Millikan	Oil drop	4.770
Perrin	Brownian movement	4.2
Regener	Charge on alpha particle	4.79
Planck	Theory of radiation	4.69
Hull and Williams	Thermionic emission	4.76
Compton	X-ray diffraction	4.804

A. S. Eddington found the formula $e = \sqrt{hc/137(2\pi)}$ in 1929 which enabled the charge of the electron to be calculated from the velocity of light and Planck's "quantum". It is a purely theoretical proposition and uses the constant 137 which is the reciprocal of Sommerfeld's fine structure constant. This provided a good check on Millikan's experimental value of 137.1, proving

it to be slightly in error. Eddington's work was based on the "exclusion theory" of Dirac.

Using a special piezoelectric quartz resonator F. Kirchner[1], in 1932, found a value of e/m_0 of $1.7590 \pm .0015 \times 10^7$.

F. G. Dunnington[2] used in 1933 the acceleration of electrons to a continuous range of velocities by a radio-frequency electrostatic field, followed by a choice of a particular velocity by magnetic field resolution, and then the measurement of this velocity through radiofrequence fields applied to a pair of accelerating slits and a pair of decelerating slits, to obtain a value of e/m of $1.7571 \pm .0015 \times 10^7$ e.m.u.

Shiba[3] in Japan later in 1933 found a value of e of $4.804 \pm .003 \times 10^{-10}$, and of e/m of $1.7602 \pm .0005 \times 10^7$.

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[1]Kirchner, F., "Determination of the Specific Charge of the Electron from Measurements of Velocity", Annalen der Physik, 12. 4. pp. 503-8, (January 21, 1932).

[2]Dunnington, F. G., "Determination of e/m for an Electron by a New Deflection Method", Physical Review, 43: 404-16, (March 15, 1933).

[3]Shiba, K., "Most Probable Values of e, e/m and h", Institute of Physical and Chemical Research, Tokyo, Scientific Papers, No. 434, pp. 128-137, (July 1933).

L. E. Kinsler and W. V. Houston[1] repeated in 1934 a measurement of e/m from the Zeeman effect of the red singlet lines of Cd and Zn. The magnetic field used was measured with an uncertainty of one part in 3000. They found a value of 1.7570 ± .0010 e.m.u.

The latest X-ray determinations of e by W. N. Bond[2] in 1935 gave values of 4.806 ± .003 and 4.805. For purposes of comparison he listed the seven most recent determinations of e/m as follows:

	1.7579 ± .0025
	1.7587 ± .0009
	1.757 ± .0015
The mean of the seven values is	1.758
1.7576 ± .0002.	1.757 ± .001
	1.7570 ± .0010
	1.7579 ± .0003

The value of e obtained from the diffraction of electrons by S. von Friesen[3] later in 1935 gave 4.796 x 10^{-10} e.s.u.

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[1]Kinsler, L. E. and Houston, W. V., "Value of e/m from the Zeeman Effect", Physical Review, 45:104-8, (January 15, 1934).

[2]Bond, W. N., "The Ratio 136/137 in Atomic Physics", Nature, 135;825, (May 18, 1935).

[3]Friesen, S. von, "Electronic Charge from de Broglie Wave-lengths of Electrons", Nature, 135:1035, (June 22,'35).

Bäcklin[1] also in 1935 determined the wavelength of the aluminum $K_{\alpha 1,2}$ X-ray line in absolute measure, finding from this the lattice constant of calcspar, giving a value of Avogadro's constant of 6.02×10^{23} with a value of 4.805×10^{-10} e.s.u. for e with a mean error of .075%.

A determination by E. Schopper[1] with an improved form of the early Rutherford and Geiger method gave a value of $4.768 \pm .005 \times 10^{-10}$ e.s.u. with a probable error of .1%. In this experiment the charge carried by a known number of alpha-particles was measured.

A more accurate repetition in 1936 of Millikan's experiment by Erik Bäcklin and Harald Flemberg[2] gave a value of e of 4.752×10^{-10} e.s.u. or with Kelström's new value of viscosity of air, which was in error in Millikan's calculations, a value of e of 4.800×10^{-10}.

In September 1936 J. W. M. Du Mond and V. L. Boll-[3]

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[1]Bates, L. F., "The Value of e", <u>Science Progress</u>, 30: 283-6, (October 1935).

[2]Bäcklin, Erik and Flemberg, Harald, "The Oil-Drop Method and the Electronic Charge", <u>Nature</u>, 137:655-6, (April 18, 1936).

[3]Du Mond, J. W. M. and Bollman, V. L., "Validity of X-ray Crystal Methods of Determining the Electronic Charge", <u>Physical Review</u>. 50:524-37, (September 15, 1936).

man used the X-ray crystal method with extremely finely powdered calcite samples, whose density was determined with a pyknometer. This gave for a value of e 4.779 ± .007 e.s.u. which was based on a scale of ruled grating wavelengths in which Cu K_{α} has a wavelength of 1.5406 x 10^{-8}.

The mass of the electron.

From the values of e/m and e, the mass of the electron may be calculated.

According to Birge in the Review of Modern Physics, mentioned before, the mass of the electron has a value of 8.994 x 10^{-28} gram.

In 1932 William Duane[1] used Bragg's formula $\lambda = 2d \sin \theta$ and Bohr's formula $cR_{\infty} = 2\pi^2 e^4 m_o/h^3$ and obtained $m_o = 9.054 \times 10^{-28}$.

L. T. Jones and H. O. Holte[2] decided in 1922 that all assumptions regarding the form of the electron in motion led to expressions such that the mass of the electron at slow velocity is a constant m_o, independent of the direction in which the inertia test is applied.

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[1]Duane, William, "The Mass of the Electron", National Academy Science Proceedings, 28:319-22, (April 1932).

[2]Jones, L. T. and Holte, H. O., "The Mass of the Electron at Slow Velocity", Science, 55:647, (June 16, 1922).

In 1901 Kaufman[1] showed experimentally that the mass of an electron could be increased by increasing its velocity sufficiently. For high velocities the mass of an electron, m, is $m_o/\sqrt{(1 - v^2/c^2)}$, where m = new mass, m_o is rest mass, v is velocity of electron, and c the velocity of light.

The size of the electron.

Charges on the surface of a sphere raise the sphere to a certain potential. The charge as a whole had a definite potential energy. If, while the total charge is kept the same, the sphere is made smaller, the charges on its surface are pushed closer and closer together, the electric potential energy is increased. The energy of a charged sphere is $q^2/2r$. The mass of an electron represents about 8.25×10^{-7} ergs of energy. This mass of the electron would be completely accounted for by its ordinary electrical energy if the electron sphere were taken of appropriate size. Substituting values in the formula $q^2/2r$ = energy gives a value of r of 1.4×10^{-5} A. This theory is attractive in so far as it explains away mass as being only the self-induction of a charged sphere. This effective radius is a

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[1] Author Unknown, "Present Status of Theory and Experiment as to Atomic Disintegration and Atomic Synthesis", Science, 73:1-5, (January 2, 1931).

a little more than 10^{-13} cm.

If we assume that the electron is a sphere with charges residing on its surface and that its rest mass is electromagnetic, we may compute its radii by the equation $m_o = 2e^2/3a$, where m_o is rest mass, e is charge in e.m.u. and a the radius.

The energy of the electron.

A comparatively slow electron, moving with a speed of 30,000 miles per second, has 250,000 times the average energy of a molecule of a gas at ordinary temperatures.

The velocity of the electron.

The Heisenberg uncertainty principle in 1927 stated that if the position of an electron is quite accurately known, then its velocity cannot be known with accuracy, and if its speed is accurately known as it passes through a given point, its direction is unknown. The speed which it has is just the speed it would have if it were governed by Newton's laws, but the inability to tell its direction is a result of the fact that it obeys the laws of quantum mechanics instead of Newton's laws.

Dr. Jesse W. M. Du Mond and Dr. Harry A. Kirkpatrick[1] at California Tech applied the Doppler principle to the

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[1] Author Unknown, "Electron Speed", Science, 74:sup. 10, (September 18, 1931).

electron scattering of X-radiation and found the average speed of invisible electrons which make up solid matter to be 1,500 miles/second for the case of carbon.

When a fast electron passes through matter, it loses its energy mainly by emission of a few large quanta of radiation. The radiation quanta are absorbed again, the absorption being due mainly to the creation of pairs. Thus, in a thick sheet of matter, a fast primary electron produces quite a number of secondary positive and negative electrons, which appear as a small shower giving rise to triple coincidences.

The frequency of the electron.

The frequency of free electrons may be obtained from the equation $mc^2 = E = hf$, where m = mass of the electron, c = velocity of light, E = electron energy, h = Planck's constant, and f = frequency. From this a value of 1.3×10^{20} is obtained for the frequency. This applies to any electron, provided it does not approach the velocity of light.

The wave properties of the electron.

In 1924 Prince Louis de Broglie[1] put forward the thesis that all material particles, and in particular, electrons, have properties analogous to those of a train

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[1]Prof. G. P. Thomson, "Electron Diffraction as a Method of Research," Nature, 135:492-5, (March 30, 1935).

of waves. This was the foundation of wave mechanics. A beam of electrons uniform in energy is regarded as replaced by a train of waves where λ = h/momentum of electron. Calculation shows that $\lambda = 10^{-8}$ cm. for electrons of 150 volts energy. It diminishes as the energy increases, being 0.7×10^{-9} cm. for 30,000 v. The wavelength is thus of the order of that of X-rays but the scattering per atom is about 10^7 times as great, corresponding to the far greater stopping and scattering power of matter for electrons than for X-rays.

The deficiencies of the particle electron theory also led de Broglie to propose the wave characteristics in doubtful cases in 1925. Because of this the Bohr electron has been replaced by a medium continuous though inhomogeneous, capable of natural vibrations. A single electron, on entering a crystal, would - on the old Bohr theory - be like a comet in a densely packed universe of solar systems and its resultant deflection would in each case be determined partially by its distance from the nucleus, and the result would be electrons coming off in all directions. This is not true, since there is a regular reflection. To have this true each electron must have its course determined by at least three electrons, probably at least five to one hundred actually, and this is highly improbable. If the beam is con-

sidered to have wave form, each wave front comes in contact with all the atoms and regular reflection results, as in X-rays, from constructive interference among the coherent secondary wave trains proceeding from the regularly arranged crystal atoms. This also explains the way in which the intensity of the reflected beam varies with the speed of the electrons and their angle of incidence.

Experiments in 1927 at the Bell Laboratories by Dr. C. J. Davisson and Dr. L. H. Germer[1] indicate that electrons may really be waves and that the wave length very nearly satisfies the relation $\lambda = h/mv$. A beam of electrons given off from a glowing electric light filament of variable positive grid of 50 to 375 volts was reflected from a crystal of nickel to a variable position collecting device, the whole being in the best vacuum attainable. They were reflected similarly to light waves, the angles of reflection and incidence being equal. This might not seem inconsistent with particles, but the distance between adjacent nickel atoms is some 250,000 times the diameter of an electron and the regular reflection of particles seems improbable. If the electrons were waves, their behavior is perfectly under-

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[1]Author Unknown, "Electrons and Wave Matter", <u>Science</u>, 67:sup. 10, (May 11, 1928).

standable for X-rays are also reflected from crystalline surfaces. Also, electrons are not reflected from poly-crystalline surfaces and neither are X-rays. Davisson and Germer showed that the observed wavelength of the electron beam was exactly that predicted by quantum theory as developed by de Broglie, E. Shroedinger and others. This wavelength equals Planck's constant of action divided by the momentum of the electron and it decreases with increasing speed.

George P. Thomson[1] of the University of Aberdeen, son of Sir J. J. Thomson, made experiments with gold-film. Electrons from an oxide-coated filament were accelerated by a high potential. Some of them passed through a small hole in the anticathode, then through a very thin film to a fluorescent screen or photographic plate. The gold film provided a screen of molecules, a lattice, and a stream of particles hitting it would strike molecules at many angles and spread out in a cone on the other side. Waves would not do that, but would bend at certain angles. This was found to be the case since the plate had a black spot in the center with concentric dark rings around it. From the geometrical dimensions of the tube, the radii of the diffraction rings

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[1]Author Unknown, "Electronic Waves", Science, 68:sup. 10, (October 12, 1928).

obtained, and the distances between the crystal planes, the wavelength of the electrons could be computed. If V is the potential in volts between the anode and the cathode, the kinetic energy of the electrons which have passed through the opening in the anticathode is given by $Ve = \frac{1}{2}mv^2$ and $\lambda_e = h/mv = \sqrt{150/V}$ angstroms. The rings were displaced by a magnet, proving they were not caused by light. So this proves that a stream of electrons is accompanied by waves, whether they are the electrons themselves or are separate from them. Their frequency is more than a million times greater than those of visible light - greater than any except that of cosmic rays. They are not like light waves but are bent by electric and magnetic fields, and their penetrating powers are different.

Drs. Eisenhut and Kaupp[1] in the laboratory of I. G. Farbenindustrie at Ludwigshafen in Germany used silver film to obtain a diffraction pattern.

There are many ways of demonstrating the usefulness of a wave conception of X-rays such as the Laue patterns and Hull, Debye-Scherer diffraction of monochromatic waves by crystal aggregates and by ruled gratings and narrow slits. The data of these experiments are avail-

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[1]Davisson, Dr. C. J., "The Wave Properties of Electrons", <u>Science</u>, 71:651-4, (June 27, 1930).

able for the calculation of electron wavelengths and these have the values predicted by de Broglie - a stream of electrons, each of momentum p, behaves as a beam of waves of wavelength inversely proportional to p, the factor of proportionality being Planck's h.

The uses of the electron.

Electron waves become a new tool to investigate the structure of matter. All that is necessary is that they should pass through the specimen to be studied without losing energy by inelastic collision. They can detect surface peculiarities impossible with X-rays. The exposure time is a matter of seconds or less, instead of hours. This process seems likely to yield important information as to the process of crystallization and the mechanism of crystal growth.

Electron waves have been used to explain many physical phenomena. The Compton effect has been treated as the interference of the X-ray wave with the electron wave. Slow moving electrons have abnormally long mean free paths. This is due to the diffraction of long electron waves around molecules.

The electron may have an elastic or an inelastic collision with an atom. If the former, it is scattered without loss of energy, and if the atoms are arranged symmetrically, Laue patterns result.

The photoelectric effect is due to the liberation, from an illuminated metal plate, of electrons which, under the influence of the electric field, pass from cathode to anode, thereby causing the photoelectric current.

The electron "microscope" was developed early in 1936 at Ohio State University by Willard H. Bennett and Paul Darby[1] of the physics department. It was the first successful production of strong narrow beams of negatively charged hydrogen atoms which can serve as "bullets" for use in atom bombardment research. Never before had anyone been able to attach extra electrons to atoms and make them stick in sufficient quantity to obtain beams of negatively charged ions. The "microscope" is a vacuum tube whose parts focus the beams of charged particles on a screen. It is so used that ions of all masses and charges can be focussed on one screen and then separated by a transverse field.

Recently C. D. Anderson and Seth H. Neddermyer[2] of California Tech discovered on Pike's Peak that electrons can smash into nuclear hearts of atoms and occasionally

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[1] Author Unknown, "Electron "Microscope" for the Study of the Atom", <u>Science</u>, 83:sup. 5, (January 17, 1936).

[2] Author Unknown, "New Types of Atom Destruction", <u>Science</u>, 84:sup. 6, (August 28, 1936).

break them up and make them eject massive particles.

Electric power companies do not charge us for amperes but for ergs or joules or kilowatt-hours. An electron at 1 volt potential can do 1.6×10^{-19} joules of work.

Perhaps one of the greatest uses of electrons is in electron tubes, and hence in radios, the sales of which amounted to almost $500,000,000 in one year. Radios are used not only for pleasure but for ship communication, and the guidance of ships and planes through fog.

Other uses are in the cathode-ray oscillograph, in phototubes for the automatic control of machinery, in high frequency oscillators used for the biological effects of high frequency radiation, and in the newer gas triode, "ignitron", which can pass currents up to 2000 amperes and is used in welding.

Attempts have been made to use electrons to produce artificial radioactivity. In one of these by J. J. Livingood and A. H. Snell[1] a filament was mounted on the high voltage side of a Sloan radio frequency resonance transformer and electrons were accelerated out of the

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[1]Livingood, J. J. and Snell, A. H., "Search for Radioactivity Induced by 800-kV Electrons", Physical Review, 48:851-4, (December 1, 1935).

vacuum tank through a thin window at a maximum energy of about 850 kV. About fifty elements have been bombarded with these electrons and examined with a Geiger counter for induced radioactivity. No positive results were obtained. This indicates that the yield is less than one activation per 10^{12} electrons of approximately 750 kV provided that the half-lives have values between some seconds and one to two hours and that the products of disintegration are electrons of over 200 kV energy. The collision cross-sections for such reactions have upper limits ranging from 10^{-35} cm.^{2} for hydrogen to 10^{-33} cm.^{2} for uranium.

An unsuccessful attempt to detect artificial radioactivity in aluminum after bombardment with electrons at 300 kV. has been reported by W. B. Lewis and W. E. Burcham.[1]

The quantum mechanics conception of the electron.

All of these effects seem on first thought to point to an electron having a more or less definite physical conception, if not of particle nature, then of wave form. And now comes the development of wave or quantum mechan-

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[1]Lewis, W. B. and Burcham, W. E., "Artificial Radioactivity by an Electron Beam and Behaviour of Newly-Made Geiger-Müller Counters", Cambridge Philosophy Society Proceedings, 32:503-5, (July 1936).

ics, which provides the best known solution of atomic processes at present. It postulates the most accurate picture of the electron as being a mathematical matrix - a difficult conception to say the least.

IV. The Alpha-Particle.

The discovery of alpha-particles.

The discovery of the radioactivity of uranium by Professor Henri Becquerel[1] in February 1896 was in a sense a direct consequence of the discovery of X-rays by Röntgen a few months earlier. The remarkable properties of the X-rays had excited intense interest throughout the scientific world, but for some time the cause and nature of these rays were a matter of conjecture. It occurred to several that the origin of the rays might be connected with the brilliant phosphorescence of the glass of the X-ray tube which appeared to accompany the emission of X-rays. Following out this idea, several investigators sought to discover whether substances like calcium sulphide, which phosphoresced under ordinary light, gave out penetrating radiations of the X-ray type. After several negative experiments of this kind,

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[1] Rutherford, Sir Ernest; Chadwick, James and Ellis, C. D., Radiations from Radioactive Substances, (1930), pp. 4-5.

it occurred to Bequerel to investigate a uranium salt, the double sulphate of uranium and potassium, which he had prepared fifteen years before and had shown to give a brilliant phosphorescence under the action of ultra-violet light. After exposure to light, the salt was wrapped in black paper and placed below a photographic plate with a small plate of silver between. After several hours' exposure a distinct photographic effect was observed, indicating the emission from the salt of a radiation of penetrating type. Subsequent experiments showed that the photographic action was quite independent of the phosphorescence and was shown equally by all the salts of uranium and the metal itself. In the light of later knowledge, it is clear that the photographic effect was due to the penetrating beta rays emitted by uranium, for the easily absorbed alpha rays did not penetrate the black paper.

Unlike X-rays the radioactive rays are of three types, known, respectively, as the alpha-rays, the beta-rays, and the gamma-rays. There are various ways of showing the existence of these various kinds of rays. Schematically if a small quantity of radium be placed at the bottom of a small hole drilled into a heavy metal block, the emerging rays can be ideally divided into the three groups by the use of a magnetic field of

suitable strength, directed at right angles to the plane of the radiations and away from the observer as he faces the block. One group is bent into a circular path to the right and will cause an impression on a photographic plate. These are the beta rays. From the direction of their deflection and the direction of the field it follows that they must be negatively charged particles. By studying quantitatively their deflection in magnetic and electric fields, it was shown that these particles are electrons which are ejected from radioactive materials with, in some cases, very high velocities, there being, in general, different groups with different velocities from any one material.

A second type of radiation is deflected by a strong field toward the left. This type consists of positively charged particles called alpha-particles, which were shown to possess a ratio of e/m much smaller than that for the beta-rays; in fact a ratio of the order of magnitude of that for atoms. These alpha-particles were found by Rutherford to have a mass of 4 and carry a charge of +2e. This identified them with the nuclei of helium atoms.

The third type of radiation, the gamma-rays, proceeds undeviated by either electric or magnetic fields, has a very high penetrating power, and is now known to

consist of electromagnetic radiations of very short wavelength lying in general in the spectral region beyond the shortest X-rays.

<u>The determination of the charge of an alpha-particle</u>.

Rutherford[1] determined the ratio E/M for alpha-particles in the following way. A fine wire coated with an active deposit of radium C, which emits alpha particles, was placed in a groove in a block within a highly evacuated vessel which was in a very strong magnetic field perpendicular to the plane of the figure. The alpha-particles emitted by the wire move with velocity v in circular paths and some of them pass through a slit and fall upon a photographic plate. The two traces resulting from reversing the field were sharp so that the radius, r, of the circular path could be quite accurately determined. This gave, since the field was known, $Hr = Mv/E$. To determine v it was necessary to measure the deflection produced by an electrostatic field. This proved to be difficult because the deflection was very small. The wire and block were arranged as in the previous experiment. Immediately over the wire were two metal plates some 5 cm. long and 0.2 mm. apart, between which could be maintained an electric field of the order of 20,000 volts/cm. The alpha particles, in passing

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[1]Richtmyer, <u>op. cit.</u>, pp. 638-41.

through this field, are deflected at right angles to their path and, by reversing the field, two lines were produced on the photographic plate. From the distance between these lines and the dimensions of the apparatus, it was possible to determine the deflection produced by the electrostatic field and thus to get a numerical value of the quantity Mv^2/E. By combining these two experiments, both E/M and v could be determined. Rutherford found that for the alpha particles from radium C, v = 2.06×10^9 cm. per second and E/M = 5,070 e.m.u./gm.

To determine M it became necessary to measure E. A known quantity of radium C was deposited on a plate P placed in a highly evacuated vessel. The alpha particles, after passing through a window of known area, and covered with very thin aluminum, fell upon a metal plate, giving to it the charge which they carried. This charge acquired by the plate in a known time was measured by an electrometer. To obtain the charge per particle it was necessary to know the number of particles. Rutherford and Geiger measured the alpha particles emitted per second by a known quantity of radium C, which was deposited on a disk which was placed inside the highly evacuated vessel at a known distance from a small circular opening of known area which was covered by a sheet of mica thin enough to allow the passage of the albha par-

ticles into a brass chamber. This chamber was evacuated to a pressure of several millimeters of mercury and had at its center an insulated wire which, by means of a battery, was maintained at a potential with respect to the walls of the cylinder just less than the critical discharge potential. When an alpha particle entered the brass chamber through the aperture, the ionization caused by the passage of the particle lowered the critical potential by an amount sufficient to allow the passage through by the cylinder of a momentary current, which could be detected by a kick in the electrometer. The charge of each particle was found to be 9.3×10^{-10} e.s.u. or + 2e. Since the neutral helium atom has two electrons, the conclusion is obvious that the alpha particles are helium nuclei. These alpha particles come from the nucleus.

The penetrating power of the alpha rays.

The alpha rays, which are very readily absorbed by thin metal foil or by a few centimetres of air, are projected from the radioactive matter with a high velocity which varies for different substances between 1.4×10^9 and 2.2×10^9 cm./sec. A thickness of .006 cm. of aluminum or mica or a sheet of ordinary writing paper is sufficient to absorb completely all the alpha rays.

Their energy.

The kinetic energy of the alpha particle expelled from a source of radium C is 1.2×10^{-5} erg.

Their detection.

Alpha particles can be detected by electrical, optical or scintillation, photographic, or expansion methods.

V. The Proton.

The discovery of the proton.

The proton was discovered in 1911 by Lord Rutherford.[1] He recognized the hydrogen nucleus as a unit particle, a fundamental building block, and he named it the "proton".

Further proof of this theory appeared when radioactive alpha particles were used to bombard hydrogen, with the result that the nucleus of hydrogen, the proton, appeared to be a fundamental building block. Prout had proposed this a century before. Thus it seemed that all the elements were built up of hydrogen nuclei and electrons.

The charge on a proton.

Since atoms were found to be electrically neutral,

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[1]Thomas, Ivor, "Stands Science Where She Did?", *Nineteenth Century*, 114:466-74, (October 1933).

and having determined that electrons carried negative charges, it remained for protons, the other particle of which atoms were composed, to carry positive charges. The charge per proton was determined to equal in value that of the electron, but to be opposite in sign.

It has been suggested more recently by Dr. M. Delbruck of the Wills Physical Laboratory of the University of Bristol that protons may have electrical charges upon them which vary in magnitude up to as much as six times the famous "e" charge.

Frederick Soddy has calculated that if a gram of protons could be gathered together and placed at one pole of the earth - another gram at the other pole, even though the repulsive force of the two falls off as the square of the distance apart, it would still be 26 tons.

<u>The mass of a proton</u>.

The mass of the proton is approximately 1840 times that of the electron, the accepted value[1] on the scale of oxygen 16.0000 being 1.00669.

<u>The size of a proton</u>.

The radius which would account for the mass of a proton is 1840 times less than 10^{-13} cm., that of the

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[1]Physics Staff of University of Pittsburgh, <u>Atomic Physics</u>, (1933), p. 247.

electron.

The velocities of protons.

Protons of hydrogen nuclei can attain a great velocity, equal to half the velocity of light, corresponding to an energy of 75,000,000 electron-volts, when they participate in cosmic ray collisions.

The uses of protons.

Before the work of J. D. Cockcroft and E. T. S. Walton[1] in April 1932 man knew no means by which he could control the creation or destruction of matter with his own weapons. They obtained protons by passing a direct current through a tube containing hydrogen. The current ionized the hydrogen atoms and electrons gravitated to the positive end of the tube and protons to the negative. The protons spilled out into a second evacuated tube, then being caught up in the current so as to be whirled through a pipe and emerge at the lower end through a mica window. The velocity of emergence depended on the current in the tube.

Arno Brasch and Fritz Lange used a high voltage "cascade" apparatus consisting of condensers connected in parallel which could be changed to series connection when set off. They used protons in this setup.

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[1]Pendray, G. E., "Men Against the Atom", New Outlook, 163:33-40, (June 1934).

The Van De Graaf generator[1] on the estate of Col. E. H. R. Greene at Round Hill, Mass., consists of aluminum balls 15 ft. in diameter, supported at a height of 24 ft. and connected by a 20 ft. vacuum tube which is 12 in. in diameter. There is 10,000,000 volts potential difference between the spheres. Into the negative end of the tube a stream of protons or deutons are admitted which will be shot to the other end by electric pressure and strike targets.

J. A. Tuves constructed an apparatus like the Van de Graaf generator but having only one sphere and a vertical tube.

Following this Drs. Edward S. Lamar and Overton Luhr[2] discovered another source of protons. An electric arc, operating in hydrogen at low pressure between an incandescent filament and a neighboring metal electrode, is surrounded by a third electrode maintained at a negative potential of a few hundred volts. The percentage of protons produced is increased approximately 90%. This source is to be applied to the Van de Graaf generator at Round Hill, Mass. These protons which are speeded at 7,000,000 volts are as effective as ordinary

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[1] Pendray, op. cit.

[2] Author Unknown, "A New Source of Protons", Science, 78: sup. 10, (December 22, 1933).

charged hydrogen molecules under twice the voltage.

The first Lawrence machine, a cyclotron, produces ten billion bullets per second. On its first test an energy of 360,000 electron-volts was used, then 510,000 and then 710,000 with lithium as the target. The number of disintegrating atoms increased as the energy increased. The one now in use has an energy of 1,200,000 e-v.

The cyclotron is composed of a very large electromagnet, the pole pieces being 80 cm. in diameter and weighing 65 tons, and constructed so as to give as uniform a field as possible. By means of an electron discharge, protons or deuterons or other ions are emitted near the center, between the two pole pieces. The ions travel in two hollow half-cylinders which are the condenser terminals of a high frequency (about 10^7 per sec.) electric oscillator. The magnetic field causes the ion to describe a half circle. If the ion arrives at the edge of one hollow half-cylinder as the other receives its maximum negative charge, the ion will be accelerated toward the negative one and again describe a half circle, but with a larger radius. The accelerating voltage times the number of half circles gives the final ion energy.

The first completely artificial transmutation[1] was

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[1]Hull, op. cit., p. 267.

carried out by Cockroft and Walton. They directed protons of only 150,000 electron-volts against lithium. The symbolic equation showing the result is:

$$_{3}Li^{7} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + {}_{2}He^{4} + E$$

One proton, H^1, enters an Li^7 nucleus and the new nucleus breaks up into two helium nuclei which are driven apart with explosive violence, each with an energy of several million electron volts. The mass difference is equal to the total energy of the two He nuclei. This affords experimental proof of the transmutation of mass into energy.

Up until 1932, then, nature was rather simple - all atoms were composed of electrons and protons, arranged in orderly array.

VI. The Neutron.

<u>The prediction of the existence of the neutron</u>.

Nearly thirty years before this time Sir William Bragg had propounded the idea of a neutral doublet to assist in the interpretation of the interaction between waves and particles. As early as April 12, 1920 W. D. Harkins[1] of the University of Chicago, and then Lord Rutherford, in the famous Bakerian Lecture to the Royal

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[1] Gray, G. W., "Discoveries Within the Atom", <u>Harpers</u>, 168:340-52, (February 1934).

Society on June 3, 1920, pointed out the reasonableness of a particle such as the neutron and predicted its mass and properties. Both said it would be composed of one proton and one electron.

The idea of the neutron was put forward formally as an "attractive speculation" by Drs. R. M. Langer and N. Rosen[1] of the Massachusetts Institute of Technology in a communication to the Physical Review of the American Physical Society on June 15, 1931. Prof. W. Pauli[2] of the Institute of Tech at Zurich, Switzerland, also suggested its usefulness in June 1931. He suggested that it might explain some fine structure in spectra and also that it might be the solution of the mystery of cosmic rays.

<u>The discovery of the neutron</u>.

More recently than that Curie-Joliot and Joliot thought they had discovered a scattering effect similar to the Compton effect when they had really discovered the neutron, but the actual credit of discovery goes to James Chadwick[3] in 1932. He bombarded the metal beryllium with fast alpha particles from radioactive polonium.

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[1]Author Unknown, "Neutrons", <u>Science</u>, 75:sup. 10, (March 4, 1932).

[2]<u>Ibid</u>.

[3]Pendray, <u>op</u>. <u>cit</u>.

A screen of nitrogen was put in the way and cloud chamber photographs taken. The nitrogen atoms were found to be propelled with an energy three times as great as was expected and particles were being emitted instead of radiation. These particles would have to be about as heavy as the proton, moving at about one tenth the velocity of light, and having no charge. They were neutrons.

W. Boethe and H. Becker had preceded Chadwick, but they guessed wrong and thought the radiation was like gamma or X-rays.

During the next year Dr. Tuve and his colleagues, L. R. Hafstad and O. Dahl, obtained results covering a variety of experiments in nuclear physics, including a verification of the existence of the neutron.

The nature of a neutron.

The neutron may be pictured as a neutral nucleus. Its atomic number is zero, its mass number 1. Its symbol is $_0n^1$. It seems the business of the neutron to bump into nuclei - not to flick off electrons from atoms. It has a ghostly existence after it leaves an atom and the collision with the atom may be elastic or inelastic. If the former, the atom bounces off with a part of the energy of the neutron. If the later, the neutron is captured, and a new atom formed or a complete disintegration may take place. The neutron was first thought

to be a close combination of proton and electron.

J. Zeleny[1] proposed that a neutron might be 1. a proton and an electron held together side by side, 2. a proton in the center of an electron, 3. a new elementary particle not related to the proton. It seems that an electron does not exist as a separate dynamical entity in a neutron. We assume, accordingly, that when a neutron is formed from a proton and an electron, the excess energy of the particles is transformed into rest mass, energy and momentum being conserved.

Dr. Franz N. D. Kurie[2] of the Sloane Physics Laboratory, Yale, concludes as a result of experiments on atomic collisions in which neutrons take part that the neutron is not a mere close combination of electron and proton acting like a fundamental particle, but is an elementary particle itself. By measuring the angles at which protons are ejected from nitrogen atoms he found that the neutron did not conform to either view held - dumbbell or onion. The direction in which either of the models would eject protons has been calculated and actual experiment agrees with neither.

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[1]Zeleny, J., "Attack on the Atom", Scientific Monthly, 37:338-43, (October 1933).

[2]Author Unknown, "The Neutron", Science, 77:sup. 8-9, (March 3, 1933).

Heisenberg proposed that a neutron is an elementary particle, but might be composed of a proton and an electron at times.

The mass of a neutron.

The mass of the neutron is considered by Chadwick[1] to be above 1.003 and probably to lie between 1.003 and 1.008. He gives the most probable value, that determined by bombardment of boron by alpha particles, as 1.0067. The validity of this value rests on the assumption that gamma-rays are not emitted in the process. Curie and Joliot[1] give a much higher value, 1.012. On the basis of values of the kinetic energy of the neutron and the mass data of Aston and Bainbridge[1] it seems that a probable lower limit of 1.0052 can be set by use of a different reaction from that of Chadwick. The average of the masses obtained by Harkins[1], Gans, Mewson, Dunning, Meitner and Philipp is 1.0059. The value of Harkins and Gans alone is 1.006.

Drs. Ernest O. Lawrence, M. Stanley Livingston and Malcom C. Henderson[2], from bombardments of beryllium with deuterons, have calculated the mass of the neutron

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[1]Harkins, William D. and Gans, David M., "The Mass of the Neutron", Nature, 134:968-9, (December 22, 1934).

[2]Author Unknown,"The Weight of a Neutron," Science, 78: sup. 8+, (November 10, 1933).

to be 1.0006 mass units, instead of the original 1.0067 as calculated by Chadwick. This means an enormous difference in energy.

All agree that it is nearly equal to the hydrogen atom, 1.0078.

The Joliot value of 1.012 would explain how protons could break up into neutrons and positrons.

Studies by Rutherford, Oliphant and Kinsey[1] in England give 1.0062, with the deuton stable, but easily decomposed, and the proton very readily breaking up into a neutron and a positron.

Lawrence and University of California investigators find the mass is 1.0003.

J. R. Dunning[2] found the mass of neutrons emitted from beryllium when bombarded by radon alpha-particles to be 1.0068.

Charles C. Lauritsen, H. R. Crane, and W. W. Harper[3] "Weighed" the neutron and found its mass to be 1.0067. This again gave strength to the theory that the neutron is a fundamental entity, going with a posi-

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[1]Author Unknown, "The Weight of the Neutron", <u>Science</u>, 78:sup. 10, (December 22, 1933).

[2]Dunning, J. R., "Emission and Scattering of Neutrons," <u>Physical Review</u>, 45:586-600, (May 1, 1934).

[3]Pendray, <u>op</u>. <u>cit</u>.

tron to form a proton.

According to Harkins if a lady's thimble could be filled with neutrons in contact, the material in it would have a weight greater than that of all the warships of all the navies of the earth.

Dr. W. J. Luyten of Harvard Observatory has calculated that a one-inch cube of neutrons weights 60,000,000 tons.

The velocity of a neutron.

With a velocity of 3×10^9 cm./sec. a neutron goes about a quarter of a mile before it experiences a sharp collision with another atom and may travel several miles before its velocity is reduced to that of ordinary molecules. Neutrons have been found with a velocity of over 30,000 miles/sec. but the velocity is usually half that. A large part of the neutrons have thermal velocities of the order of 2×10^5 cm./sec.

The ionizing power of neutrons.

Light is thrown on the behavior of the neutron by the cloud chamber investigations of Feather, Dee[1] and others. It is comparatively easy to obtain large numbers of tracks produced by atoms recoiling from neutrons because the neutron itself produces almost no ions at all in traversing an expansion chamber of ordinary di-

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[1]Physics Staff of University of Pittsburgh, op. cit., p.247.

mensions. Dee states that the ionization along the path of the neutron is less than one ion pair per 3 m. of air. Accordingly vast numbers of neutrons may be allowed to enter the Wilson chamber during the time of photographic exposure and then, although the probability that a single one will interact with a nucleus is small, there is a fair chance of obtaining a record of a recoil nucleus or a disintegration collision in a single expansion.

Feather has found that neutrons can produce a variety of disintegrations in nitrogen. There is evidence that in some collisions the neutron is captured and an alpha-particle ejected - the residual nucleus being an isotope. He also succeeded in disintegrating oxygen with neutrons, a feat which has never been accomplished with alpha-particles or fast protons.

Urey and later Bartlett were able to account for most of the observed isotopes of the light elements by supposing that in building up a nucleus we should add protons and neutrons alternately. This scheme fails at He^4 but is all right from Li^6 to O^{16}. Above this protons and neutrons must be added two at a time.

The size of the neutron.

Dr. George Braxton Pegram[1] and associates at Col-

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[1]Author Unknown, "New Tools", Time, 28:50+, (August 1, 1936).

umbia have set the neutron diameter at one ten-trillionth of an inch. The principle size of small particles can be determined mathematically according to the way they scatter when striking heavier substances. For the neutron this gives a radius of 1.2×10^{-13} cm.

The energy of a neutron.

The maximum energy of a neutron (with a mass of 1.010) ejected from beryllium by alpha-particles from polonium should be about 9×10^{6} e-v. Fermi and others showed that neutrons passing through substances containing hydrogen lose their energy by collisions with protons. So long as the energy of the neutron is higher than the energy with which the protons are bound in the molecules of the substance through which the neutrons pass, it seems evident that the latter give, on the average, half their energy to the proton at every collision.

The absorption of neutrons.

We have to assume that the capture probability will in general be a complicated function of neutron velocity, depending upon the special features of the nuclear model. Since the absorption cross-section for neutrons is, for many elements, larger than the nucleus cross-section, it is possible that the neutrons may be captured in energy levels outside the nucleus. This would at

once explain why for many elements the cross-section is larger for slow neutrons than for fast neutrons, and further would account for the selective absorption effects observed by Dr. Szilard. The absorption of slow neutrons is believed to take place in two ways; a general absorption of very slow neutrons (thermal energies) together with a highly specific absorption of faster neutrons.

Cooled paraffin wax absorbs slow neutrons more strongly than paraffin at room temperature.

<u>The production of neutrons</u>.

Drs. Charles C. Lauritsen, Richard Crane and Andrew Soltan[1] at California Tech have produced neutrons artificially in greater quantities than before known. They used metal beryllium, disintegrated with artificial alpha rays which had been given a push of half a million volts. Slow neutrons, under a million volts of energy, but penetrating two inches of lead, were produced. This was the first time neutrons were produced without the aid of radioactivity.

In bombarding light elements with alpha-particles, neutrons have been detected from all elements up to aluminum, except for helium, nitrogen, carbon, oxygen.

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[1] Author Unknown, "Artificial Production of Neutrons", <u>Science</u>, 77:sup. 8, (January 27, 1933).

Irene Curie, F. Joliot and P. Preiswerk[1] found that bombarded phosphorus gave off neutrons for as much as three hours after the bombardment had ceased.

Prof. L. M. Mott-Smith and Dr. T. W. Bonner[2] succeeded in making atoms shoot off neutrons. They bombarded targets of calcium fluoride, boron and beryllium with alpha particles, obtaining thus liberated neutrons. The neutrons could then hit gas atoms in a Wilson Cloud Chamber with the result that photons were driven out. The range of the photon tracks was a measure of the neutron energy. In no case were neutrons given off in constant energy groups. In fluorine there were five different groups of neutrons, in boron eight, and in beryllium over twenty.

Neutrons obtained from bombardments give a means of determining energy levels within nuclei.

One of the best sources of neutrons is a platinum capsule filled with powdered beryllium and from 500 to 2000 millicuries of radon. Alphas from the radon strike beryllium atoms and neutrons and gamma rays are emitted. The gamma-rays are absorbed by .75 mm. of lead. The

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[1]Author Unknown, "Neutrons from Artificially Radioactive Elements", Science, 80:sup. 5, (August 24, 1934).

[2]Author Unknown, "Energy within Atoms", Science, 80: sup. 5, (August 24, 1934).

number of neutrons emitted is 4×10^6/sec. Slow neutrons are several times as efficient as fast ones.

The cyclotron will probably produce more neutrons than could be produced by the entire radium supply of all the laboratories in any country.

Kurie at the University of California, bombarding beryllium with deuterons at 2 M. E. V. obtains 10^9 neutrons/sec.

Neutron capture.

A typical result of the experiments with high-speed neutrons is the great probability that a collision with a nucleus of not too large atomic number will give rise to the ejection of an alpha-ray or a proton, accompanied by the capture of the neutron and the formation of a nucleus of a new element which, in general, will possess beta-ray radioactivity. The effective nuclear cross-sections for collisions with such effects are in fact of the same order of magnitude as the cross-sections responsible for simple scattering of high-speed neutrons by nuclei, which in turn agree with ordinary estimates of nuclear dimensions. Another typical experimental result is the surprisingly great tendency even for a fast neutron in collision with a heavy atom to attach itself to the nucleus with the emission of gamma-radiation and the formation of a new isotope which may be

stable or radioactive according to the circumstances. In fact, for processes of this kind, cross-sections are found which, although several times smaller, are still of the same order of magnitude as nuclear dimensions. The phenomena of neutron capture thus force us to assume that a collision between a high-speed neutron and a heavy nucleus will in the first place result in the formation of a compound system of remarkable stability. The possible later breaking up of this intermediate system by the ejection of a material particle, or its passing with emission of radiation to a final stable state, must in fact be considered as separate competing processes which have no immediate connection with the first stage of the encounter.

The uses of neutrons.

Using neutrons, Fermi (in Rome) has excited radioactivity in many heavy elements - phosphorus, iron, silver, arsenic, uranium, etc. The neutron was added to the nucleus.

Neutron rays are ten times more potent than X-rays in their effects on living tissue and organisms. They annihilate white blood corpuscles. Prof. Ernest Orlando Lawrence of the University of California whose apparatus produces a beam of 10,000,000 neutrons a second, finds that on the white blood cells of rats neutrons ex-

ert ten times the destructive effect of X-rays of equal energy.

A neutron of mass 2.

A neutron of mass 2 was considered as a theoretical possibility by Harold Walke[1] in 1933. And in 1935 S. Flügge[2] stated that there are a large number of indications showing that a conglomeration of two neutrons with antiparallel directed spins plays an actual part in the structure of the nucleus.

In any element the nucleus is composed of a number of protons equal to the atomic number and a number of neutrons given by the difference between the mass number and the atomic number. Isotopes differ only in the number of neutrons.

The atomic nuclear spin data obtained from the analysis of fine structures in line spectra show that odd atomic weight atoms have nuclear spins. There are two groups of odd atomic weight atoms, namely, those with odd and those with even atomic charges. The nuclei of the first group contain an odd number of protons and the nuclei of the second an odd number of neutrons. A

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[1]Walke, Harold, "Existence of a Neutron of Mass 2", Nature, 132:242-3, (August 12, 1933).

[2]Flügge, S., "Is There a Neutron of Mass 2?", Zeitschrift fur Physik, 95. 5-6. pp. 312-18, (June 17, 1935).

significant experimental fact is that all the nuclei in the first group have positive nuclear spins, while the nuclei of the second group can exhibit either positive or negative spin values. It seems possible to account for the negative and positive spins of the members of the second group mentioned by postulating the existence of two types of nuclear neutrons, namely; (a) a proton and an electron, (b) a negative proton and a positron. Atoms with remaining odd neutron type (a) will exhibit positive nuclear spin - those of type (b) will exhibit negative spin. It is assumed that the negative protons exist only in the bound state of neutrons when they are in the nucleus.

VII. The Positron.

The discovery of the positron.

C. D. Anderson[1] of California Tech discovered the positron on August 2, 1932. It had been foreshadowed a year earlier in the theory of the mathematician Dirac although he tried to tie his proposition to the proton and without much success. He called it an anti-electron. Anderson's discovery was confirmed in the Cavendish Laboratories presided over by Lord Rutherford. A vertical cloud chamber with an intense horizontal mag-

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[1]Eldridge, *op. cit.*, p. 324.

netic field of 17,000 gauss and a current of 1600 amperes at 250 volts in water-cooled copper tubes was being used. Cosmic ray particles were being used as the bombarding particles. A plate was obtained having a track of a particle of the dimensions of an electron which passed through a 6mm. lead plate, and which, because of its curvature, could not have had a negative charge, but instead, a positive one. Anderson concluded that the tracks he obtained had to be due either to positive particles comparable to electrons in mass, or else the chance occurrence of independent tracks so as to indicate a common point of origin of two particles and the latter possibility on a probability basis did not seem likely.

Positrons can be obtained at will by bombarding a lead plate with neutrons from beryllium and also as a result of induced radioactivity.

The name oreston was suggested for the positron by Herbert Dingle.

The nature of the positron.

From the fact that positrons occur in groups associated with other tracks, it is concluded that they must be secondary particles ejected from an atomic nucleus. If we retain the view that a nucleus consists of protons and neutrons (and alpha-particles) and that a neutron

represents a close combination of proton and electron, then from electromagnetic theory as to origin of mass the simplest assumption is that an encounter between the incoming primary ray and a proton may take place in such a way as to expand the diameter of the proton to the same extent as that of an electron. This would release an energy of a billion electron-volts appearing as a secondary photon. As a second possibility the primary ray may disintegrate a neutron (or more than one) in the nucleus by the ejection either of an electron or a positron with the result that a positive or negative proton remains in place of the nucleus, without the emission of a photon. This postulates a negative proton for which there is no proof. If the neutron proves to be a fundamental particle of a new kind, this theory would not hold and the proton would then consist of a neutron and a positron. Evidence appears to be in favor of the view that a positron is produced by the decomposition of a photon on colliding with a nucleus.

Artificial radioactivity discovered by the Joliots may show that positrons are contained in atoms themselves. Experiments by bombardment also show that twin electrons, one negative and one positive, are created from radiant energy in the field of influence of the atom outside the nucleus.

It is well known that when positrons are annihilated, gamma-rays with a quantum energy of about 500 e-v. are emitted. This seems to prove that annihilation occurs with a loosely bound electron as a partner of the disappearing positron, the process involving mainly low energy positrons. In the process of positron annihilation there is really an emission of two quanta in opposite directions, as required by the law of conservation of momentum.

Since there is certainly no room, in atomic theory, for the permanent existence of positive electrons well outside a nucleus, then a positive electron that comes from there must be born there, and if born there, an equal negative electron must be born simultaneously in order to conserve electric charge. The phenomenon of "showers" seems thus to represent the birth of multiple pairs of positive and negative electrons as a result of one or more collision processes induced by the primary radiation.

<u>The production of positrons</u>.

The passage of beta-rays through matter is accompanied by the emission of positrons. In addition to the formation of "pairs", (electron and positron) the absorption of the primary beta-particle is sometimes accompanied by the emission of a single positron. In

aluminum this is the predominating effect.

Positrons may be produced by gamma-ray bombardment of metals. The number of positives per one hundred negatives as found by the Joliots is in uranium 40, in lead 30-35, in copper 18, and in aluminum 5. They supposed each positron to come from a photon transmuting itself into a positive and a negative electron. The photon must have a minimum energy of 1,000,000 e-v.

<u>The life of a positron</u>.

Positrons suddenly pop out of space only to disappear as suddenly, usually combining with an electron to form radiation. The life of a positron is only .000,000,000,36 sec., but this is long enough for it to be seen in a cloud chamber.

<u>The energy of positrons</u>.

Positrons which are emitted by newly radio-activated elements form a continuous spectrum of a maximum energy of 1.5×10^6 e-v. for nitrogen, 3×10^6 for phosphorus and approximately 1.5×10^6 for selenium according to Curie and Joliot.

J. Zeleny obtained positrons by subjecting atoms to gamma radiation from radium. He obtained some with energies as high as 800,000,000 e-v. which come either direct from outer space, or are ejected from atoms by the action of cosmic rays.

An artificial source of positrons is produced by a fast beam of protons of about 300 kV. energy incident on a thin lithium sheet in an aluminum hemisphere. An expansion chamber and a photographic plate are used in connection with this.

The charge and mass of a positron.

The charge and mass of the positron are found to equal those of the electron to within 5%. It is impossible to determine any but approximate values.

Impacts of positrons on all substances give an intense X-ray radiation.

The energy of positrons.

In passing through matter positrons lose energy more rapidly than electrons. The energy of positrons produced in gamma-ray bombardment confirms the idea that an electron and a positron are produced simultaneously according to Chadwick, P. M. S. Blackett and G. Occhialini at the Cavendish Laboratory.

VIII. The Neutrino.

The prediction and theory of the neutrino.

Some years ago Fermi[1] perceived that when a nuclear impact knocked a neutron and a positron out of an atom,

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[1]Author Unknown, "New Tools", Time, 28:50+ , (August 17, 1936).

there was a mysterious disappearance of energy. He surmised that the excess energy rode away on a little particle which, now generally accepted as theoretically necessary, still eludes observation. It is because of Fermi that this little particle, the neutrino, has an Italian name.

H. Bethe and R. Peierls[1] also put forward the view that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar(\hbar = h/2\pi)$ exists, and that this "neutrino" is emitted together with an electron in beta-decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics. Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus, or (b) as being created at the time of emission. According to (a) one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (b) the rules of neutron and proton would be symmetrical and one would expect that positive electrons could also sometimes be created together with a neutrino in nuclear transformations.

In the theory of beta-decay as proposed by Fermi one assumes the existence of elementary processes in

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[1]Bethe, H. and Peierls, R., "The 'Neutrino'", <u>Nature</u>, 133:532, (April 7, 1934).

which a neutron is transformed into a proton by simultaneous creation of an electron and a neutrino. For the inverse process, one needs the previous existence of an electron and a neutrino. It might therefore be thought that a proton cannot be transformed into a neutron without the presence of a neutrino source. Such a source, however, is not necessary if it be admitted that in empty space all negative neutrino states are occupied in the same way as thenegative energy states of the electron in Dirac's theory of the positron. In this case, the presence of an electron alone is sufficient since the neutrino can be furnished from a negative state.

A theory has been developed by P. Jordan and R. de L. Kronig[1] in which an attempt is made to reduce the field of radiation with light quanta to a field of particles with spin, obeying the statistics of Dirac and Fermi. These particles have been tentatively identified with neutrinos, the occurrence of which must be postulated in radioactive beta-disintegrations in order that energy and angular momentum may be conserved. If the neutrino theory of radiation has a physical signi-

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[1] Kronig, R. de L., "The Neutrino Theory of Radiation and the Emission of β-Rays", <u>Nature</u>, 137:149, (January 25, 1936).

ficance, the experimental result just mentioned calls for a very particular type of interaction between the heavy particles (proton and neutron) of which the nucleus is built up and the light particles (electrons, positrons and neutrinos) created during the beta-disintegration. In fact the interaction energy must be such that the neutrino field excited by the disintegration process is of the radiationless type.

Attempts at detection of the neutrino.

Although it seems very unlikely that neutrinos, after having been emitted in a nuclear process, give rise to any detectable ionization, Bethe and Peierls point out that it is not impossible in principle to decide experimentally whether they exist. One possible experiment would be to check the energy balance for the artificial beta-decay. A second way would be to observe the recoil of the nucleus in beta-decay. If the neutrino hypothesis is correct, there would be a defect of momentum which would be uniquely connected with the lack of observable energy in each individual process.

In an attempt to detect the neutrino a source of 7 mg..of radium D + E + F, surrounded by 95 mm. of lead, 11 cm. from the centers of two Geiger-Müller counters connected in parallel and shielded on all sides by 45 mm. of lead, the whole being placed 30 m. below the sur-

face of the earth, was used. It was found that neutrinos did not produce as much as one primary ionization in passing through 35,000 km. of air and they cannot have a magnetic moment greater than 2.5×10^{-4} Bohr magneton. The number of ions produced by a neutrino, if its magnetic moment is n Bohr magnetons, is shown to be $103\ n^2$/km. in air at N. T. P. and is practically the same whether the mass of the neutrino is assumed to be nil or equal to that of an electron.

From experimental results on the shape of the upper portion of a continuous beta-ray spectra of thorium C and thorium C" the distribution of energy is deduced. This distribution is compared with Fermi's theory wherein the shape of the curve depends on the mass of the neutrino. The comparison supports Fermi's conclusion that the mass of the neutrino is zero or certainly not more than a very small fraction of the electronic mass.

If u, V, V' are the velocities of an electron, proton and neutron and m, M, M' their respective masses, then $M' = M - m + (m/\sqrt{(1 - u^2/c^2)} - m)$ and the term in brackets corresponds to the neutrino.

IX. The Anti-Neutrino.

An anti-neutrino has been proposed in mathematical theory but there is no experimental evidence of its ex-

istence as yet.

X. The Deuteron.

The discovery of the deuteron.

Dr. Harold Clayton Urey[1] of Columbia University announced the discovery and isolation of heavy hydrogen and heavy water in 1932. He, along with Brickwedde and Murphy, noticed a very faint satellite in the Balmer lines of hydrogen, displaced from the main lines like the lines of ionized helium, but not quite so far. They thought perhaps it was a ghost. So they liquified hydrogen and subjected it to fractional distillation, and the satellite was stronger.

They have also obtained H^3 in very small quantities by bombarding deuterons with deuterons. There is one part in a billion in normal hydrogen.

The charge and mass of the deuteron.

The deuteron, the name given to the nucleus of the heavy hydrogen atom, had the charge of a proton but approximately double its mass. It is presumably a proton-neutron combination. The positive mass affords a handle to hurl it. It also has a wavelike nature. Both neutron and proton may be some distance from the deuteron's

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[1]Rusk, R. D., "New Frontiers of Science", Scribner's Magazine, 98:210-4, (October 1935).

center of mass. In collision the neutron enters the atomic nucleus and joins it and the proton goes on alone. This accounts for the change to higher weight and the emission of a proton in transmutations employing deuterons.

Uses of deuterons.

The whirligig atom-gun or cyclotron invented by the modern alchemists Dr. Lawrence, and his colleagues Dr. M. Stanley Livingston and Malcom C. Henderson, has been used with deuterons, stepping them up to a speed corresponding to 3,000,000 volts. These atomic bullets have been used to bombard targets of platinum, brass, wax and many other chemicals. One kind of fragment flies out with a speed corresponding to 5,400,000 volts. This is 2,400,000 volts more than the deuteron bullet speed and the fragment is a proton. The companion fragment to the proton is the neutron. This flies out with 2,400,000 electron-volts energy. The deuteron may be itself broken up with the liberation of 4,800,000 electron-volts energy. The best targets gave only two disintegration protons for every 10,000,000 deuteron bullets bombarding the target.

The Princeton cyclotron[1], in construction in 1936,

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[1]Author Unknown, "Cyclotron at Princeton", Science, 83: sup. 8, (March 13, 1936).

also using protons and deuterons with a velocity of 19,000 miles a second, will have a breastwork of earth and perhaps water tanks in addition to protect the operators. Two vacuum tubes which produce high-frequency oscillations at 20 meters and will require 50 to 60 kw. (as much power as is used by large broadcasting stations, but taking place inside the magnet and so having no effect on radio reception) will be used. Drs. Malcom C. Henderson, instructor in physics at Princeton University and Milton C. White, a National Research Council fellow at Princeton, are the designers. The pole pieces will be 35 in. in diameter. Those at California Tech are 27 in.

Crane, Lauritsen and Soltan found that deuteron bombardment of beryllium releases 500 times as many neutrons as alpha particle bombardment. Beryllium turns into boron and lithium to helium when bombarded with deuterons.

XI. The Negative Proton.

To explain why the central nucleus of many kinds of atoms sometimes spins one way and sometimes the other, the negative proton (already mentioned) has been postulated. It has been suggested by Dr. S. Tolansky of the Imperial College of Science, London. Prof. George Gam-

ow[1] also said it would be most helpful in explaining many of the difficulties regarding the stability of certain atoms, like beryllium. The negative proton cannot be discussed theoretically in a way similar to Dirac's positron, however.

It seems in the light of symmetry that it may exist, but it is as yet only a theory.

XII. Summary.

The composition of matter has long been an intriguing subject to all thinking people. The earliest records we have of speculation on the subject are from the Greek philosophers, the chief among these being Leucippus and his pupil, Democritus, who lived in the fifth century B. C.

Nothing more of any very practical nature was done until 1803 when John Dalton formulated the modern chemical atomic theory. The theory as it then existed stated that all matter was composed of atoms, which were indivisible. Later in the same century various men began to doubt the finality of atoms, and proposed yet smaller divisions. The first to prove the existence of one of these smaller particles, the electron, and to measure

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[1]Author Unknown, "A Possible Negative Proton", Science, 80:sup. 6, (July 27, 1934).

its charge and mass, was J. J. Thomson. Millikan carried out the same calculations using a different set-up. Since then there have been many determinations in many different ways. The electron in its first conception seemed to be a particle, having definite size and shape. Around 1925 Louis de Broglie proposed that the electron had,not particle characteristics, but those of waves. Soon after this experimentation by Davisson and Germer seemed to give confirmation of this. Then recently has come a quantum mechanics conception of the electron which gives it no physical existence at all, but instead, that of a mathematical matrix. So now we seem to be almost as much in the dark as before - we are pretty sure than an electron is - but what is it?

Almost at the same time as the discovery of the electron, Becquerel discovered the phenomenon of radioactivity, which gave rise to a new atomic constituent, the alpha-particle which was identified with the nucleus of the helium atom.

In 1911 Rutherford discovered the proton, which is identified as the nucleus of the hydrogen atom. It has recently been found to serve well in the capacity of a bullet in atomic destructions and transmutations.

The structure of matter seemed, then, to be quite simple, being explained as an orderly and logical arrange-

ment of protons and electrons, differing in number in each element.

However, early in 1932 came the discovery of first the neutron, by Chadwick, and then the positron by Anderson. The neutron had been predicted by several men before its discovery. It is a particle having the mass of a proton but no charge. It seemed first that it must be composed of a proton and an electron. Current opinion seems to be rather that the neutron is a fundamental particle and the proton is a composite of a neutron and positron. Whatever its composition, however, the neutron also plays an important part in atom bombardment.

The positron has the mass of an electron, but the opposite charge, and as yet has no particular use.

Fermi noticed that in some atomic transformations there was a disappearance of energy. To explain this he proposed a particle called the neutrino, having no mass and no charge. As yet there is no proof other than theoretical of its existence, nor of the recently proposed anti-neutrino for opposite processes.

In the same year that the neutron and the positron made their debut, Urey announced the discovery, or rather the isolation, of heavy hydrogen. The nucleus of the heavy hydrogen or deuterium atom has been named the deu-

teron, and it likewise is used in the various forms of atom guns now employed in atomic research.

In the light of symmetry, then, there is apparently one particle missing - one having the mass of a proton, but the opposite charge. Such a particle has an existence, but purely in theory, as yet.

Thus we see today, not a simple picture or explanation of matter, but instead a more complex situation than ever before, which is quite hazy in spots, and full of speculations and theories, yet becomes more fascinating with each new development.

Name	Discoverer	Year	Experiment	Charge	Mass	Size	Reference for discovery
Electron	Thomson	1897	Deflection in vacuo.	$e = 4.770 \times 10^{-10}$ e.s.u. (latest value is 4.800)	9.054×10^{-28} gm.	10^{-13} cm.	Richtmyer, Introduction to Modern Physics.
Alpha-Particle	Becquerel	1896	Radioactive disintegration.	9.3×10^{-10} e.s.u. or +2e	4		Rutherford, Chadwick and Ellis, Radiations from Radioactive Substances.
Proton	Rutherford	1911	Alpha-particle bombardments.	+e	1.0069 (on basis of O = 16)	1840 times less than that of electron	Thomas, "Stands Science Where She Did?", Nineteenth Century, (October 1933)
Neutron	Chadwick	1932	Alpha-particle bombardment of beryllium.	Neutral	1.0067	One ten-trillionth of an inch	Pendray, "Men Against the Atom", New Outlook, (June 1934).
Positron	Anderson	1932	Cosmic ray bombardments in a Wilson Cloud Chamber.	+e	Same as electron to within 5%	Same as electron	Eldridge, Physical Basis of Things.
Neutrino	Fermi	1932	Disappearance of energy in atomic reactions.	Neutral	Nil	Nil	"New Tools", Time, (August 19, 1936).
Deuteron	Urey, Brickwedde, Murphy	1932	Satellite in Balmer series of hydrogen.	+e	Double that of proton		Rusk, "New Frontiers of Science", Scribner's Magazine, (October 1935).

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